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MEMORANDUM REPORT ARBRL-MR-03198

BASELINE EVALUATION OF THE TDNOVA CODE

Albert W. Horst

September 1982

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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Past attempts to simulate two-phase flow phenomena in high-performance, bagged-charge artillery using one-dimensional, two-phase flow interior ballistic codes were met with only limited success, presumably because of the inability of these models to capture configural complexities associated with the charge-chamber interface. The recent development of a fully two-dimensional, axisymmetric, two-phase flow model (TDNOVA) provides for the first time an explicit treatment of two-dimensional flamespread in bagged

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charges. Functioning of the basepad and centercore ignition system are included within the physical scope of the model, as is the influence of parasitic charge components which may exhibit exothermic or endothermic properties as well as resistance to gas- and solid-phase flows.

Baseline calculations are presented which demonstrate excellant agreement between TDNOVA and its one-dimensional predecessor NOVA for an appropriate, dimensionally degenerate, bagged-charge problem. Further calculations using TDNOVA, based on an axisymmetric representation of a 155-mm howitzer, are shown to reveal an acceptably small level of sensitivity to a reasonable range of values for various user-definable parameters, such as mesh size.

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I. INTRODUCTION

Several recent reports[1-4] have described progress made over the past several years in an effort to develop a fully two-dimensional, two-phase flow interior ballistic model. This work has focussed on the process of flamespread through the propelling charge as a hydrodynamic problem and on the influence of the path of flamespread on the formation of potentially dangerous pressure waves in the gun chamber. The effort was, to a large extent, motivated by the fact that early successes in simulating these phenomena in Navy cased-ammunition guns[5,6] with one-dimensional, two-phase flow models were not reproduced when Army bagged-charge artillery became the subject of study[7]. The presence of circumferential ullage external to the bag apparently offered, at least during the very early stages of the interior ballistic cycle, a region of high permeability capable of altering the flame path and equilibrating longitudinal pressure gradients -- a process totally outside the scope of the one-dimensional representation. A subsequent quasi-two-dimensional treatment[8] recognizing this possibility rapidly led the way to a fully two-dimensional representation known as TDNOVA, the subject of this report.

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[1] *P.S. Gough, "Two-Dimensional Convective Flamespreading in Packed Beds of Granular Propellant," ARBRL-CR-00404, USA ARRADCOM, Ballistic Research Laboratory, Aberdeen Proving Ground, MD, July 1979. (AD#A075326)*

[2] *A.W. Horst and P.S. Gough, "Modeling Ignition and Flamespread Phenomena in Bagged Artillery Charges," ARBRL-TR-02263, USA ARRADCOM, Ballistic Research Laboratory, Aberdeen Proving Ground, MD, September 1980. (AD#A091790)*

[3] *P.S. Gough, "A Two-Dimensional Model of the Interior Ballistics of Bagged Artillery Charges," ARBRL-CR-00452, USA ARRADCOM, Ballistic Research Laboratory, Aberdeen Proving Ground, MD, April 1981.*

[4] *A.W. Horst, F.W. Robbins, and P.S. Gough, "A Two-Dimensional, Two-Phase Flow Simulation of Ignition, Flamespread, and Pressure-Wave Phenomena in the 155-MM Howitzer," ARBRL-TR- , USA ARRADCOM, Ballistic Research Laboratory, Aberdeen Proving Ground, MD, (not yet released).*

[5] *A.W. Horst, T.C. Smith, and S.E. Mitchell, "Key Design Parameters in Controlling Gun-Environment Pressure-Wave Phenomena - Theory Versus Experiment," 13th JANNAF Combustion Meeting, CPIA Publication 273, Vol. 1, pp. 341-368, December 1975.*

[6] *A.W. Horst and P.S. Gough, "Influence of Propellant Packaging on Performance of Navy Case Gun Ammunition,"* Journal of Ballistics*, Vol. 1, No. 3, pp. 229-258, 1977.*

[7] *A.W. Horst, C.W. Nelson, and I.W. May, "Flame Spreading in Granular Propellant Beds: A Diagnostic Comparison of Theory to Experiment," AIAA Paper No. 77-856, AIAA/SAE 13th Propulsion Conference, July 1977.*

[8] *P.S. Gough, "Theoretical Study of Two-Phase Flow Associated with Granular Bag Charges," ARBRL-CR-00381, USA ARRADCOM, Ballistic Research Laboratory, Aberdeen Proving Ground, MD, September 1978. (AD#A062144)*

II. TECHNICAL DISCUSSION

A. Description of TDNOVA

The TDNOVA code provides an unsteady, two-dimensional, axisymmetric, two-phase flow representation of the interior ballistic cycle. As mentioned previously, the development of TDNOVA was undertaken largely in response to the configural complexities associated with the use of bagged artillery charges, such as the 155-mm, M203 Propelling Charge depicted in Figure 1. Flamespread through bagged charges is believed to be strongly influenced by the details of the ullage which initially surrounds the bag and by the behavior of the bag material itself. Accordingly, an explicit representation is made in TDNOVA of the two-phase region occupied by the propelling charge at any time. The flow in the ullage, which surrounds the region occupied by the propellant, is treated as unsteady, inviscid, and single phase.

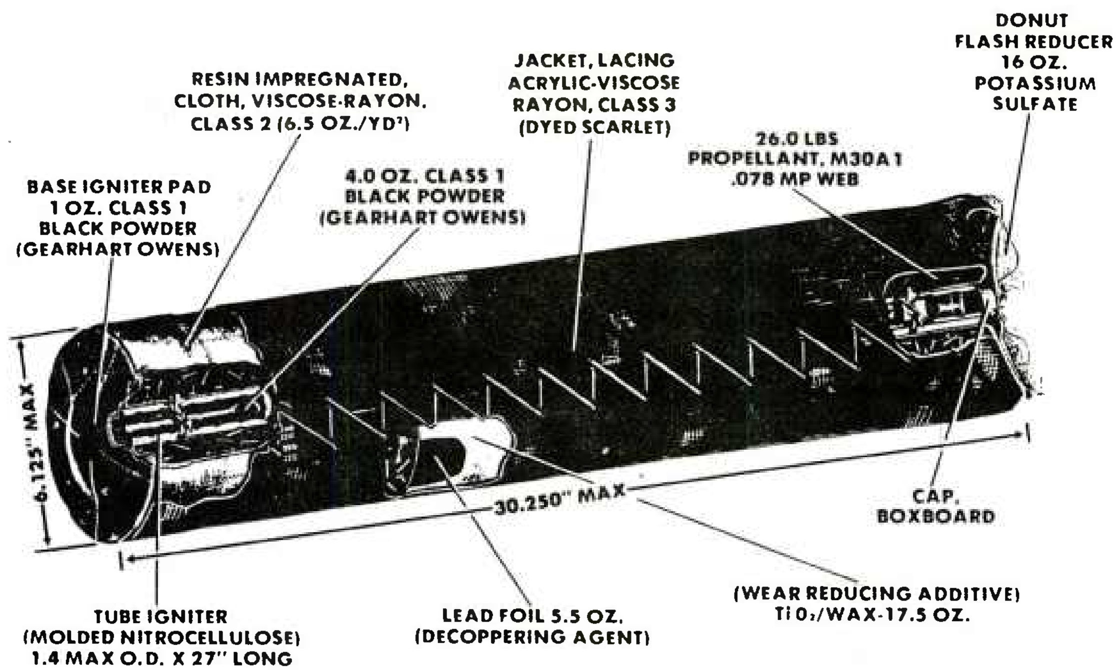


Figure 1. 155-mm, M203 Propelling Charge

The ullage is divided into several disjoint regions, coupled to one another and to the two-phase flow in the propelling charge by means of finite jump conditions at all their mutual boundaries. By formulating the theory in such a manner as to use directly the jump conditions at the boundary, a mechanism is provided for representation of the influence of the bag. Impermeability is reflected directly within the momentum jump condition as a quasi-steady flow loss. Similarly, the influence of exothermically or endothermically reactive components, such as igniter basepads, centercore tubes, or wear-reducing liners, may be reflected by means of source terms in the mass and energy jump conditions.

The division of ullage into the several regions depicted in Figure 2 is based on the instantaneous configurations of the external boundaries (e.g., spindle face, chamber/tube sidewall, and projectile base) and the propelling charge itself. Each region of ullage may be treated as lumped parameter, quasi-one-dimensional (i.e., one-dimensional-with-area-change), or two-dimensional, in accordance with user-definable criteria based on physical dimensions.

As suggested earlier, representation of a basepad igniter or centercore tube may be treated within the structure of the bag. A centercore ignition charge, coaxial with the bag, may also be included in the representation as a quasi-one-dimensional, two-phase flow, coupled to the state of the flow within the bag and any ullage present at the ends of the chamber by reference to finite jump conditions. Representation of the ignition train also admits specification of an externally injected stimulus of predetermined flow rate and energy.

Initially, TDNOVA provides a fully two-dimensional analysis of flow within the two-phase region occupied by the propellant bed. However, in all calculations performed to date, the regions of ullage contiguous to the bag have been treated as quasi-one-dimensional, the continuum coordinate being defined by the common boundary. Corner regions of ullage are then given a lumped-parameter treatment. Figure 3 illustrates this level of representation.

Following the completion of flamespread, rupture of the bag sidewall, and equilibration of the radial structure of the pressure field to within some user-specified limit, a quasi-two-dimensional approach is introduced, similar to that reported previously[8]. For the duration of the ballistic cycle, the propelling charge is given a quasi-one-dimensional representation, as is the circumferential ullage, while regions of axial ullage at the ends of the chamber are treated as lumped parameter (see Figure 4).

Each of these regions of continuous flow is mapped onto a regular figure, a unit line or square, by means of a boundary-fitted-mesh-transformation algorithm. The method of solution is then based on an explicit, two-step marching scheme which utilizes characteristic forms of the balance equations at both external and internal boundaries. A detailed description of the code has been provided by Gough[3]. The reader is further directed to an earlier discussion of application of TDNOVA to the 155-mm, M203 Propelling Charge by Horst et al[4].

In the sections that follow, we provide a description of several series of baseline calculations performed to assist in evaluation of the operational capabilities of TDNOVA.

B. Comparison with NOVA

A direct comparison was made between results predicted by TDNOVA and by its quasi-one-dimensional predecessor NOVA[9]. An appropriate data base, a dimensionally degenerate representation of the previously described bagged-

[9] *P.S. Gough, "The NOVA Code: A User's Manual. Volume 1. Description and Use," IHCR 80-8, Naval Ordnance Station, Indian Head, MD, 30 December 1980.*

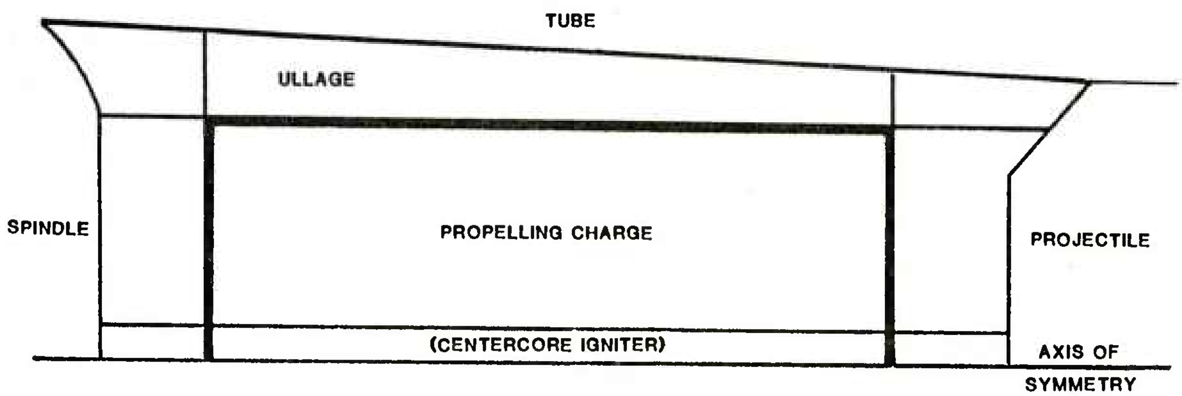


Figure 2. Computational Regions of TDNOVA

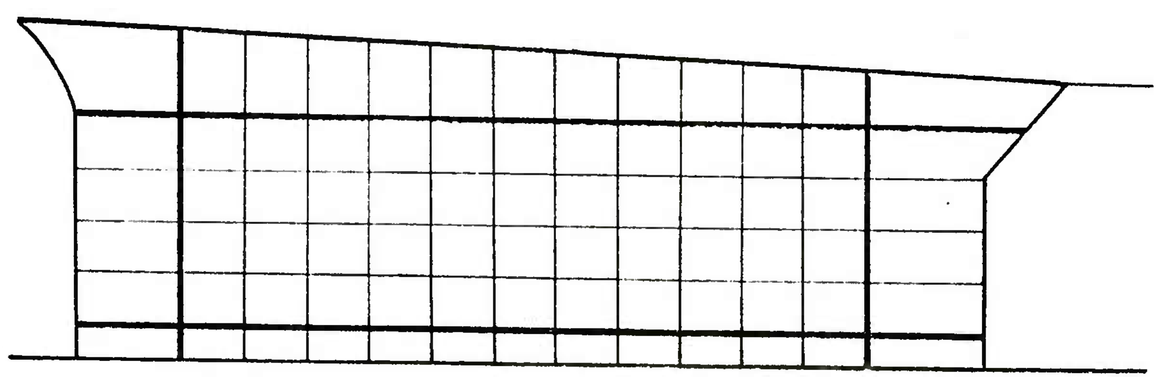


Figure 3. Two-Dimensional Mesh of TDNOVA

charge problem, was devised by suppressing the presence of both centercore igniter and circumferential ullage. Bag sidewall and centercore tube characteristics thus played no role in the problem. Further, the basepad was replaced by a predetermined, one-dimensional ignition stimulus. The resulting problem is depicted schematically in Figure 5. A summary of required input data for both NOVA and TDNOVA is provided in Appendix A.

It is noted that, in accordance with criteria based on size and structure of the flow, the NOVA code may assign a continuum representation, in the axial direction, to regions of ullage at either end of the chamber. Calculations were performed using the NOVA code both unaltered and with a modification introduced to maintain a lumped-parameter representation for these regions, similar to that provided by TDNOVA after transformation to the quasi-two-dimensional representation. In both cases, the NOVA simulations employed 30 axial stations, while a 30x7 mesh was used for the TDNOVA runs. Finally, a TDNOVA calculation was performed with the quasi-two-dimensional representation invoked from time zero. In the absence of circumferential ullage, this last TDNOVA treatment was geometrically equivalent to that of the modified NOVA code.

A summary of results is provided in Table 1. All values for maximum chamber pressure fall within 2% of one another, while those for muzzle velocity fall within 1%. Values for $-\Delta P_i$, the initial reverse pressure difference between breech and forward ends of the chamber, represent small differences between large numbers and are not appropriately compared in the same fashion. Rather, we choose to compare the entire pressure-difference versus time profiles in Figure 6. Similarly, we display a comparison of axial flamespread profiles in Figure 7. We note a favorable level of agreement for all parameters.

TABLE 1. SUMMARY OF NOVA/TDNOVA RESULTS

CODE	MAX PRESSURE (MPa)	MUZZLE VELOCITY (m/s)	INITIAL REVERSE PRESSURE DIFF (MPa)
NOVA (30x1 mesh)	323	814	-26
NOVA - modified treatment of end ullage (30x1 mesh)	325	816	-21
TDNOVA (30x7 mesh)	328	820	-21
TDNOVA (30x1 mesh)	327	820	-21

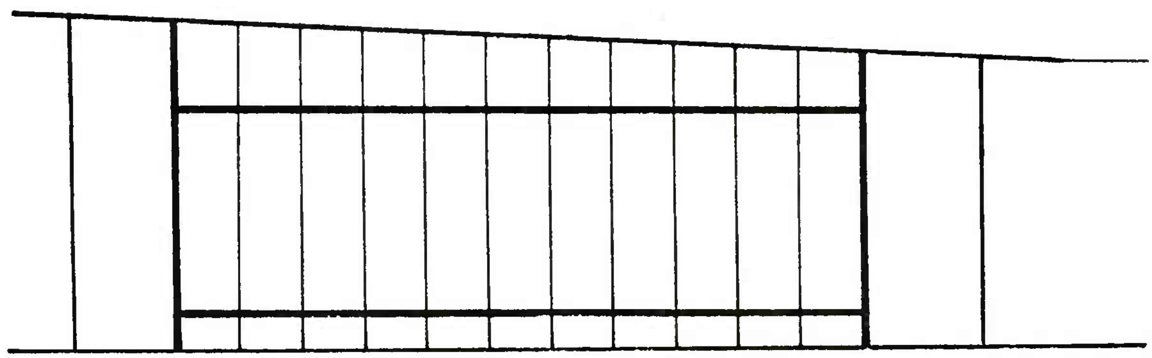


Figure 4. Quasi-Two-Dimensional Mesh of TDNOVA

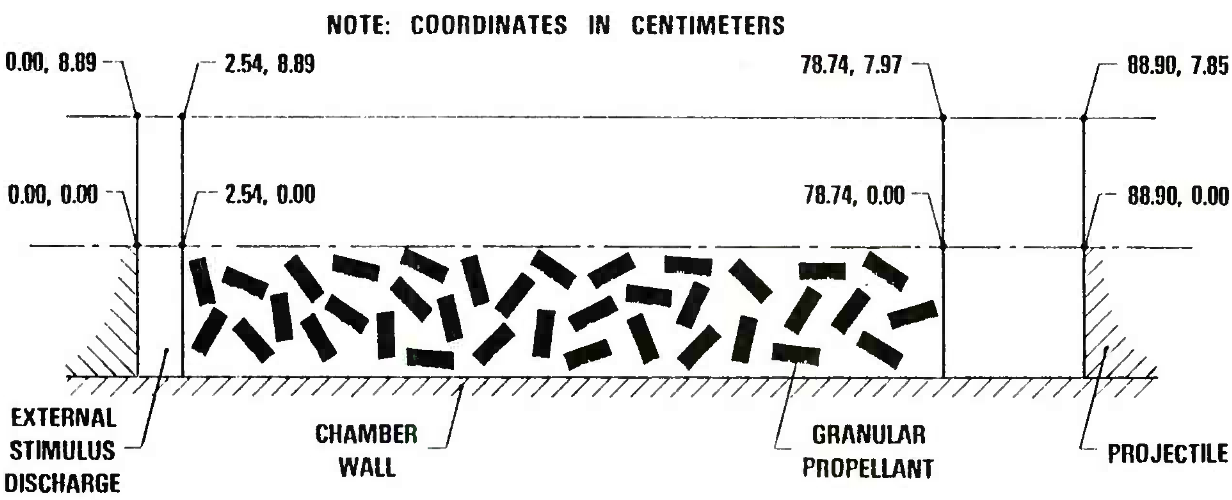


Figure 5. Schematic Representation of Quasi-One-Dimensional Test Problem

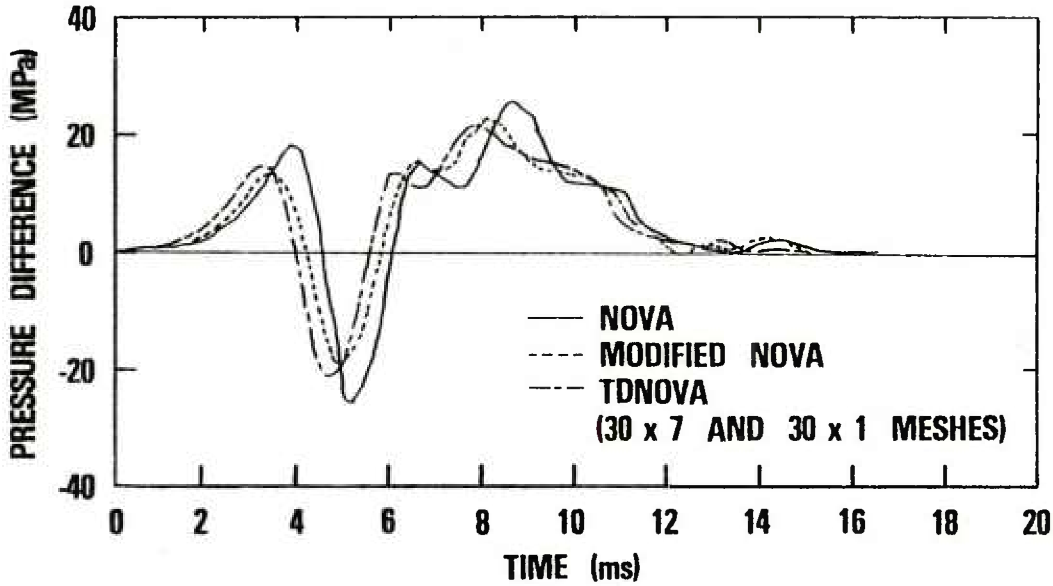


Figure 6. NOVA and TDNOVA Predictions of Pressure Difference Versus Time

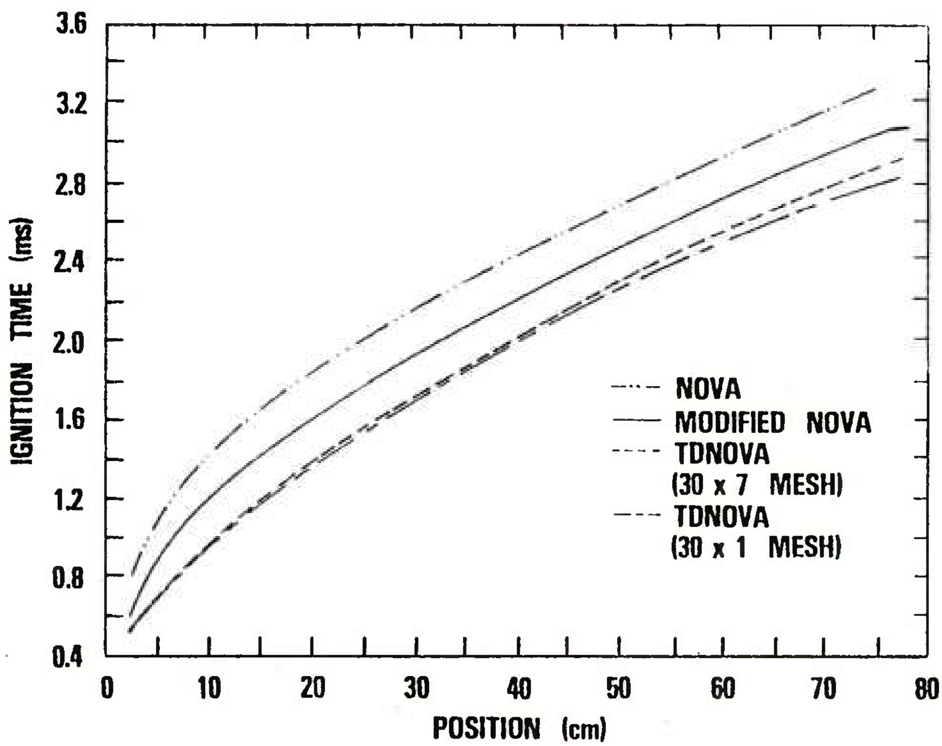


Figure 7. NOVA and TDNOVA Predictions of Axial Flamespread

C. Influence of P_{tol} Criterion

We noted earlier that, upon completion of flamespread, rupture of any bag sidewall material present, and equilibration of the radial structure of the pressure field to within some user-specified limit, TDNOVA introduces a quasi-two-dimensional approach for the duration of the calculation. This transformation is invoked in the interest of economy and, in consideration of the scope for which TDNOVA is intended, appears to be well motivated. The particular criterion employed involves P_{tol}, a parameter which is compared, at each axial location, to the difference in values for the pressure at the tube wall and centerline, divided by the value at the tube wall. When this quantity becomes less than P_{tol} at all axial stations, the transformation takes place.

As this transformation carries with it a number of assumptions[3] required to establish a quasi-one-dimensional description of flow within the two-phase medium, we undertook to determine the influence of P_{tol} on the remainder of the solution. A previously established data base[4] (see Figure 8 and Appendix B) for the 155-mm, M203 Propelling Charge was employed, with P_{tol} varied over a wide range of values. Results are summarized in Table 2, and a comparison of pressure-difference versus time profiles is displayed in Figure 9. All values of P_{tol} equal to or greater than 0.05 yielded identical results, as the time for the final point of bag rupture became the controlling parameter, prohibiting transformation at any earlier times. Even for values of P_{tol} as small as 0.005, results remain virtually unchanged. Pressure and temperature fields, at the instant of transformation, are compared in Figures 10 and 11. Little difference in structure is noted for the various conditions. Prediction of flamespread is, of course, totally unaffected by P_{tol}, its completion being a requirement for transformation.

TABLE 2. INFLUENCE OF P_{tol} ON TDNOVA RESULTS

P_{tol} (and time of transformation, ms)	MAX PRESSURE (MPa)	MUZZLE VELOCITY (m/s)	INITIAL REVERSE PRESSURE DIFF (MPa)
0.005 (3.51)	365	842	-3
0.010 (3.49)	363	842	-3
0.050 (3.19)	363	842	-2
>0.050 (3.19)	363	842	-2

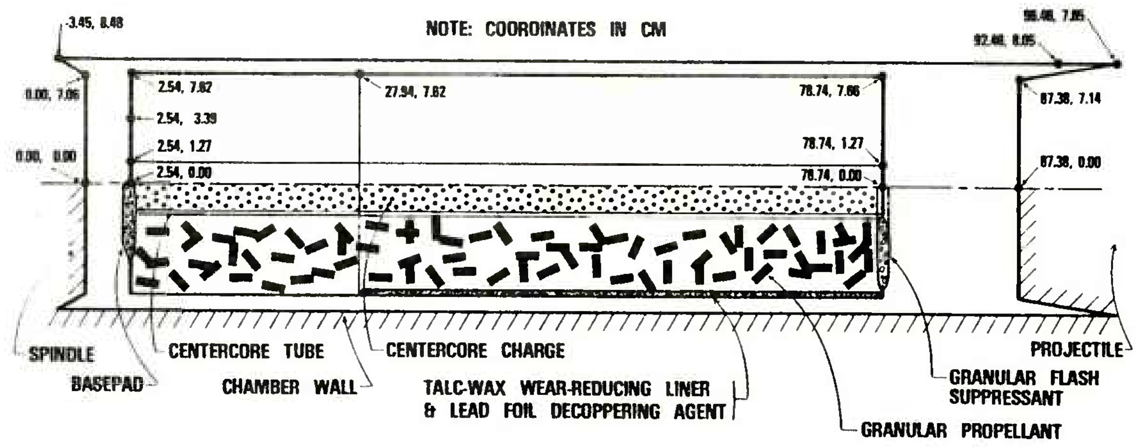


Figure 8. Schematic Representation of 155-mm, M203 Propelling Charge

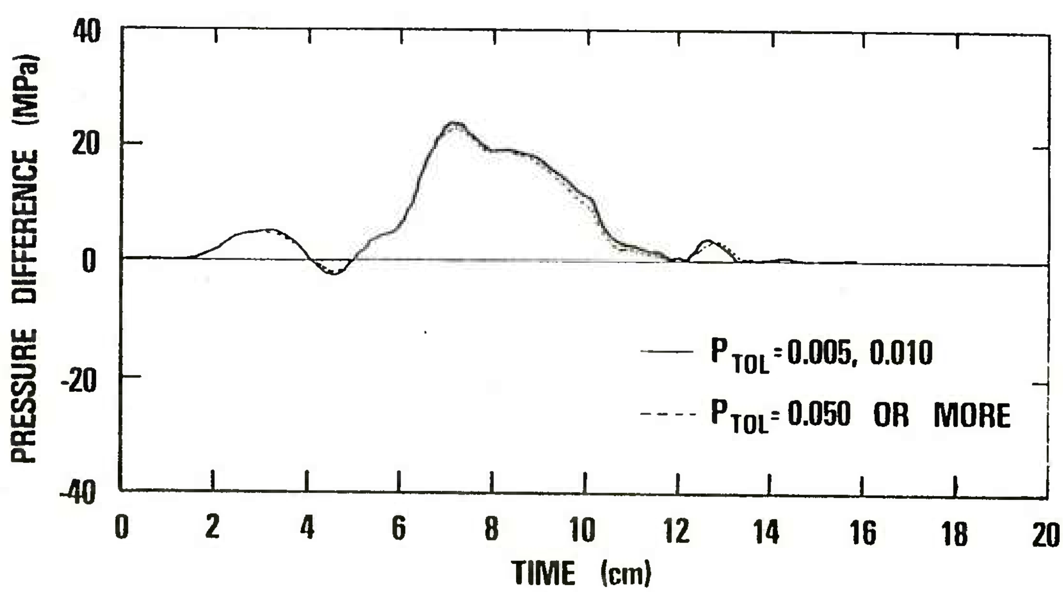


Figure 9. Influence of P_{tol} on TDNOVA Predictions of Pressure Difference Versus Time

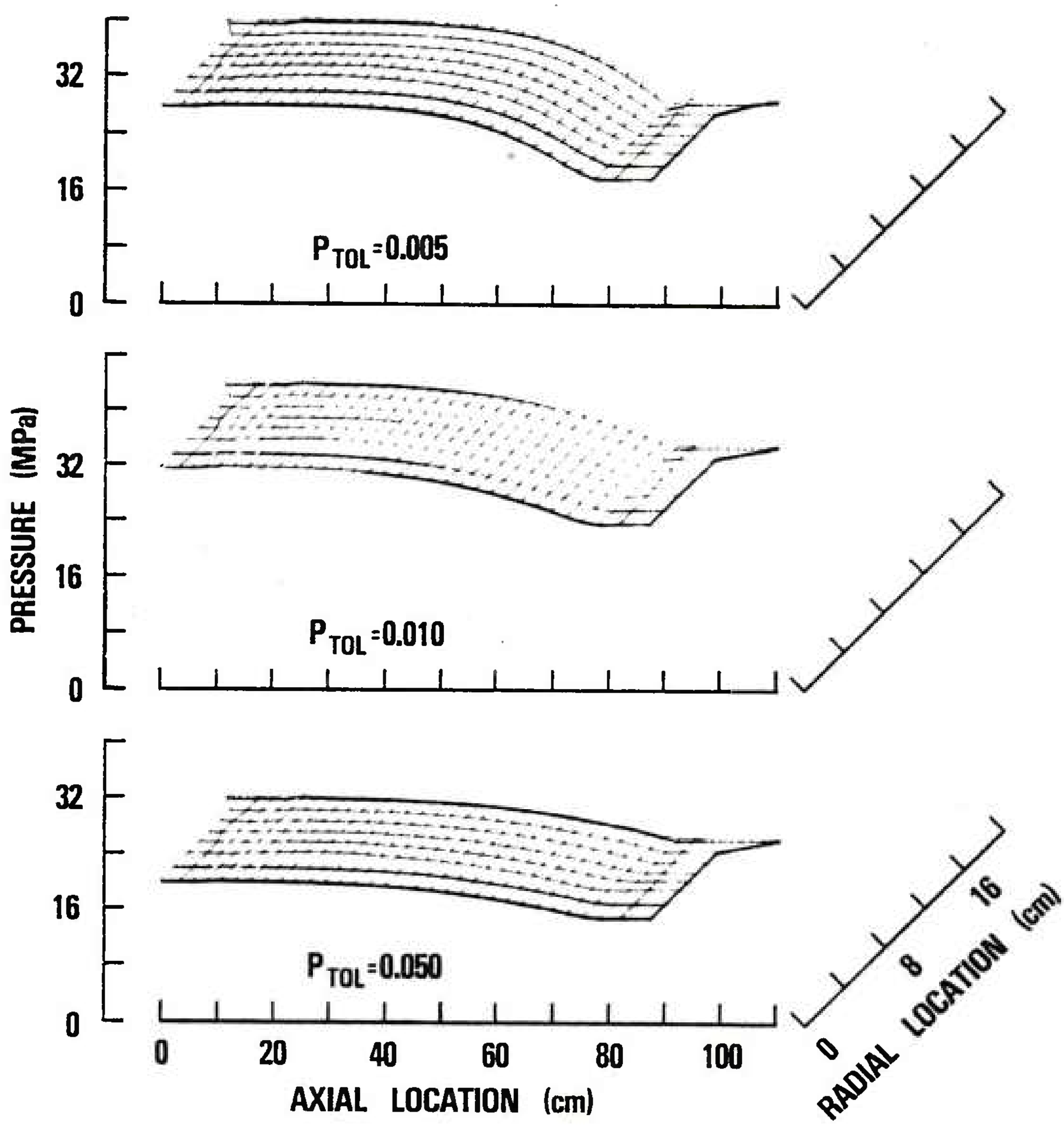


Figure 10. TDNOVA Predictions of Pressure Fields at Times of Transformation for Several Values of P_{tol}

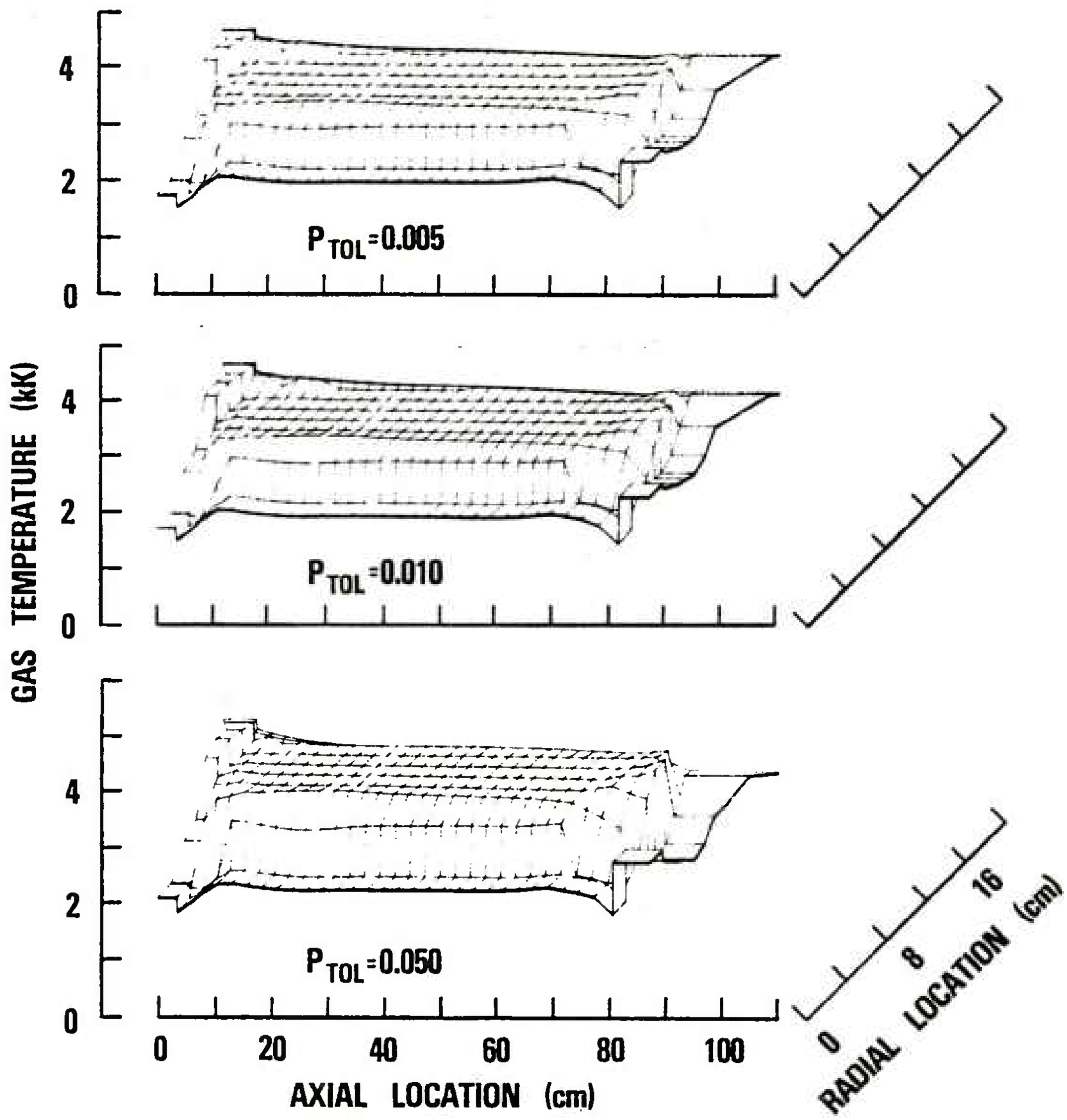


Figure 11. TDNOVA Predictions of Temperature Fields at Times of Transformation for Several Values of P_{tol}

D. Influence of Mesh

To complete this baseline evaluation of TDNOVA, attention must also be directed to the sensitivity of solutions to the mesh employed to represent the two-dimensional, two-phase region of flow. The input data base provided in Appendix B was again selected for this phase of the study. From 10 to 35 axial mesh points and from 3 to 9 radial mesh points were employed to represent the region occupied by the propellant bed. While not fundamentally linked to the limitations imposed by the macroscopic nature of the governing equations for TDNOVA, a selection of mesh size somewhere in the range studied is certainly compatible with both the intended purpose and physical scope of TDNOVA. Further, in the case of any extensive propelling charge design studies, the need for economy may also limit one to this range of values.

A summary of results from these calculations is provided in Table 3. We note some apparent dependence of predicted performance on the number of radial mesh points, though the total spread is less than 4% for values of maximum chamber pressure and less than 2% for those of muzzle velocity. As before, the initial reverse pressure difference, being calculated as the difference of two large numbers, exhibits a large percentage but small absolute variation. Selected pressure-difference versus time profiles, flamespread contours, and pressure field plots are displayed in Figures 12 through 16.

TABLE 3. SUMMARY OF TDNOVA RESULTS FOR VARIOUS MESHES

MESH (axial pts x radial pts)	MAX PRESSURE (MPa)	MUZZLE VELOCITY (m/s)	INITIAL REVERSE PRESSURE DIFF (MPa)
20x3	357	836	-3
25x3	354	834	-3
30x3	357	836	-3
35x3	358	836	-4
10x5	359	838	-3
20x5	359	838	-4
25x5	363	839	-3
30x5	359	830	-5
35x5	356	831	-7
20x7	362	840	-2
25x7	364	843	-2
30x7	363	842	-3
35x7	366	835	-3
20x9	364	842	-2
25x9	368	845	-1

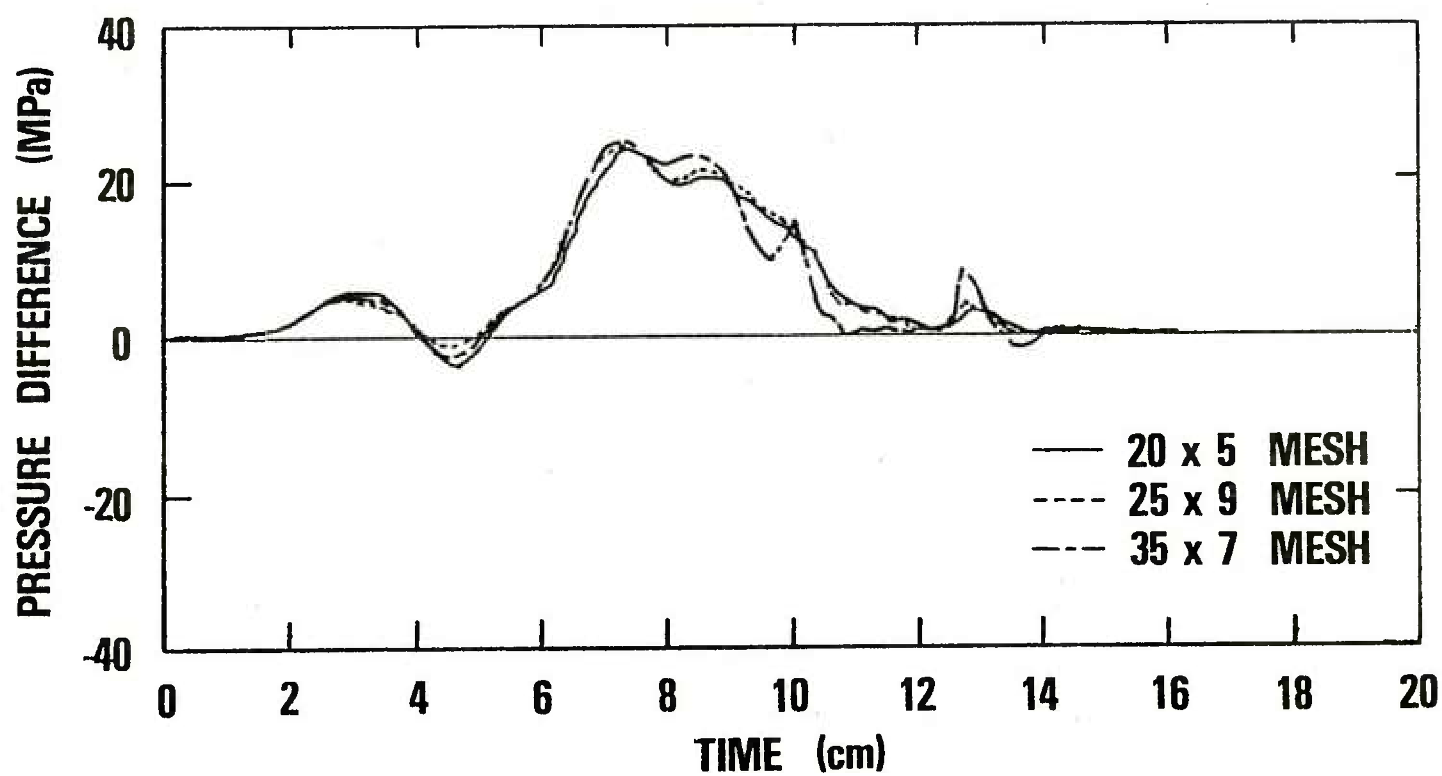
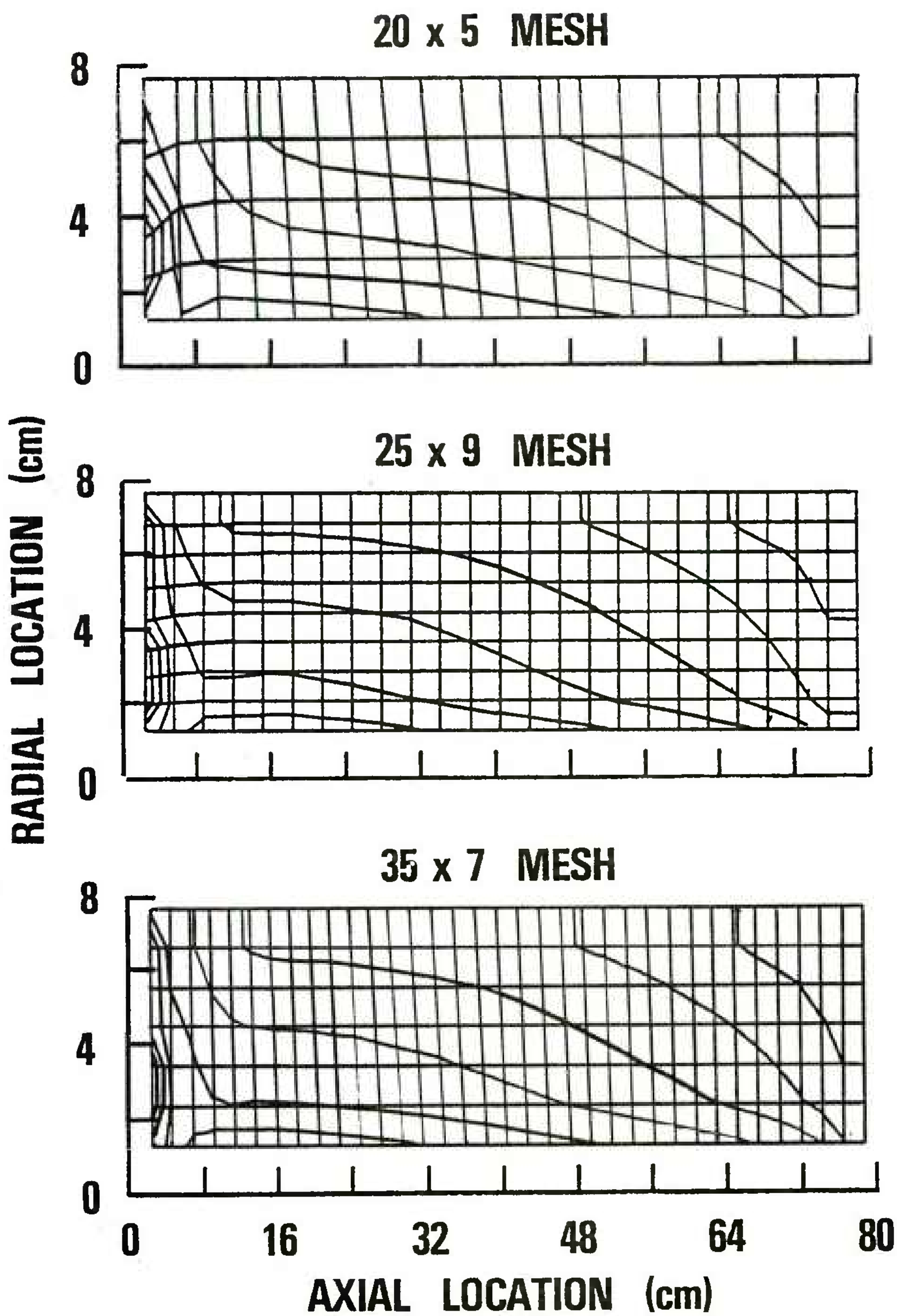


Figure 12. TDNOVA Predictions of Pressure Difference Versus Time for Various Meshes



Note: flame contours displayed every 0.24 ms

Figure 13. TDNOVA Predictions of Flamespread for Various Meshes

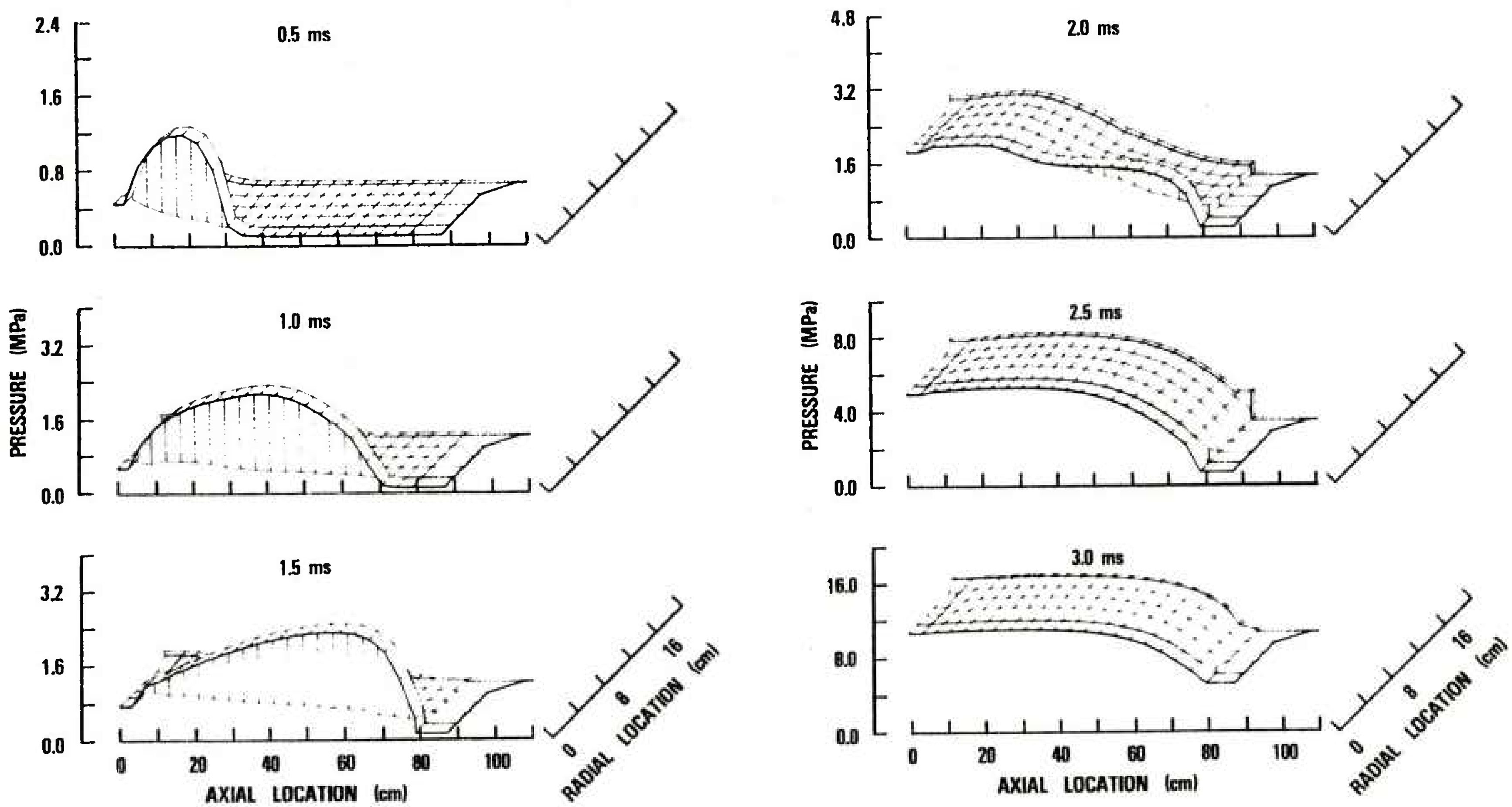


Figure 14. TDNOVA Prediction of Pressure Fields for a 20x5 Mesh

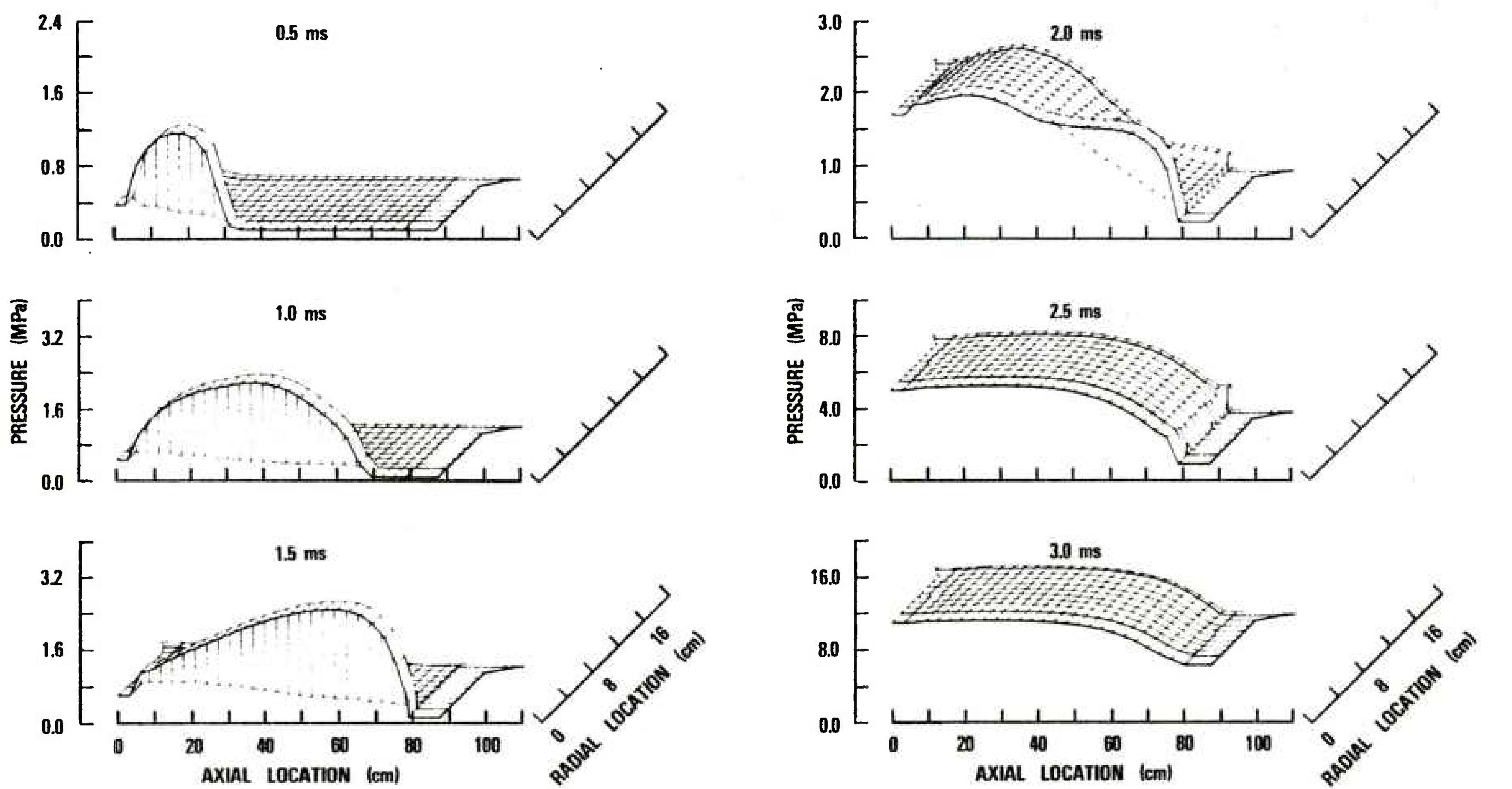


Figure 15. TDNOVA Prediction of Pressure Fields for a 25x9 Mesh

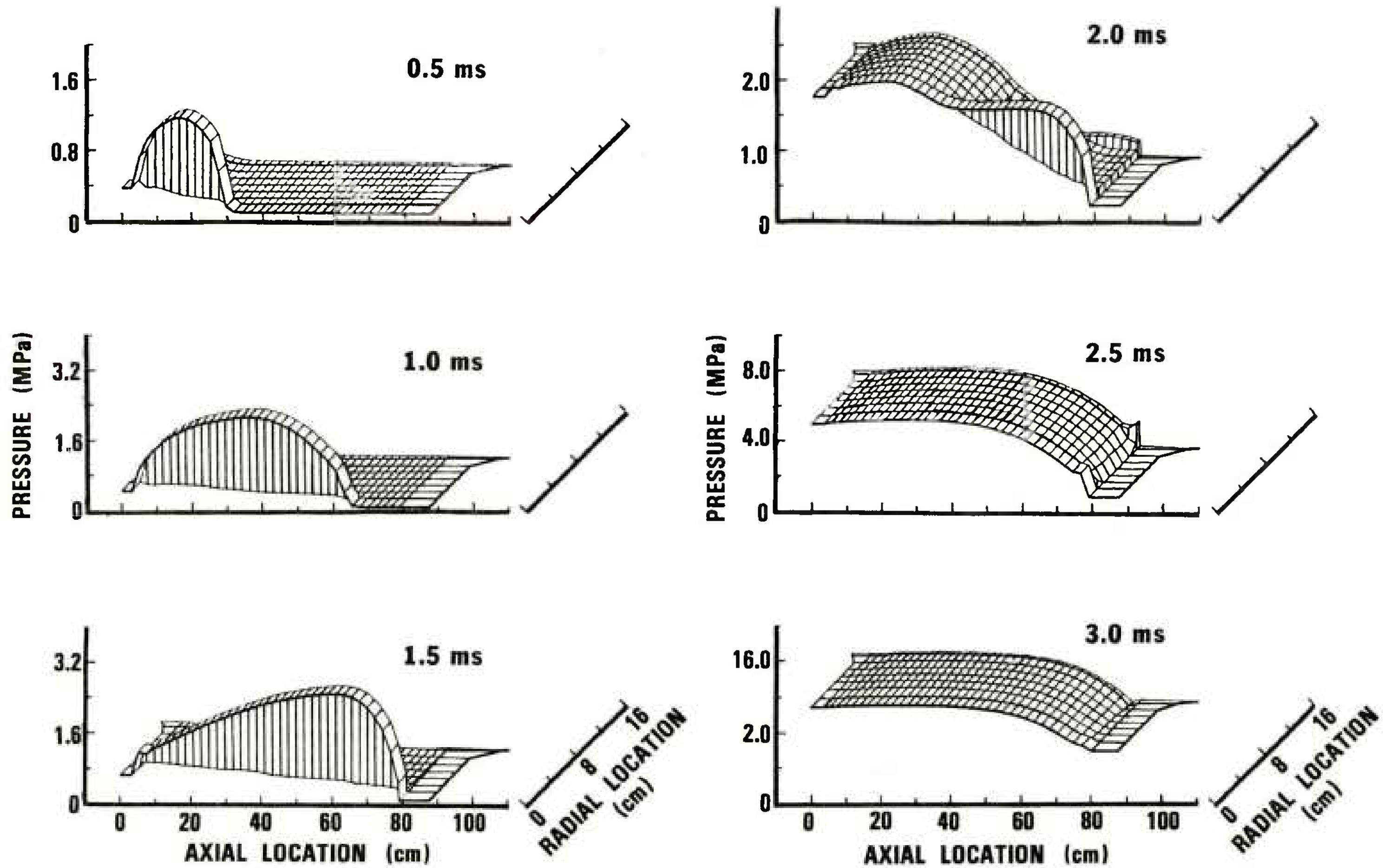


Figure 16. TDNOVA Prediction of Pressure Fields for a 35x7 Mesh

III. CONCLUSIONS

In an effort to provide a baseline evaluation of the TDNOVA code, several series of calculations were performed. Based on the results of these calculations, the following conclusions can be drawn:

1. Simulations of a quasi-one-dimensional propelling charge obtained using TDNOVA and NOVA, its quasi-one-dimensional predecessor, are essentially equivalent. When TDNOVA is modified to introduce an immediate transformation to its quasi-two-dimensional mode and when NOVA is also modified to maintain a lumped-parameter representation of regions of axial ullage, results from the two codes become virtually identical.

2. For at least one, relevant, bagged-charge problem, results provided by TDNOVA are only minimally influenced by the value selected for P_{tol}, a parameter used to identify adequate equilibration of the radial pressure field before transformation to a quasi-two-dimensional representation of flow is allowed. Antecedent requirements for bag rupture and completion of flamespread apparently allow substantial equilibration of radial pressures prior to application of the P_{tol} criterion.

3. A limited study of the influence of mesh density on TDNOVA results failed to demonstrate absolute convergence of results; nevertheless, the variation in predicted quantities was shown to be acceptably small for a number of meshes covering the current range of practical interest.

ACKNOWLEDGMENTS

The author is grateful to Dr. P.S. Gough of Paul Gough Associates, Inc. and to Mr. F.W. Robbins of the Ballistic Research Laboratory for their assistance in implementing the required modification to the NOVA code.

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1. P.S. Gough, "Two-Dimensional Convective Flamespreading in Packed Beds of Granular Propellant," ARBRL-CR-00404, USA ARRADCOM, Ballistic Research Laboratory, Aberdeen Proving Ground, MD, July 1979. (AD#A075326)

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4. A.W. Horst, F.W. Robbins, and P.S. Gough, "A Two-Dimensional, Two-Phase Flow Simulation of Ignition, Flamespread, and Pressure-Wave Phenomena in the 155-MM Howitzer," ARBRL-TR- , USA ARRADCOM, Ballistic Research Laboratory, Aberdeen Proving Ground, MD, (not yet released).

5. A.W. Horst, T.C. Smith, and S.E. Mitchell, "Key Design Parameters in Controlling Gun-Environment Pressure-Wave Phenomena - Theory Versus Experiment," 13th JANNAF Combustion Meeting, CPIA Publication 273, Vol. 1, pp. 341-368, December 1975.

6. A.W. Horst and P.S. Gough, "Influence of Propellant Packaging on Performance of Navy Case Gun Ammunition," <u>Journal of Ballistics</u>, Vol. 1, No. 3, pp. 229-258, 1977.

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9. P.S. Gough, "The NOVA Code: A User's Manual. Volume 1. Description and Use," IHCR 80-8, Naval Ordnance Station, Indian Head, MD, 30 December 1980.

APPENDIX A

INPUT DATA FOR NOVA/TDNOVA COMPARISON CALCULATIONS

NOTE: The NOVA code was developed prior to the introduction of the International System of Units (SI) and employs English units throughout. A summary of conversion factors required to effect conversion to SI units, employed in TDNOVA, is provided below.

TO CONVERT	FROM NOVA UNITS	TO TDNOVA UNITS	MULTIPLY BY
LENGTH	in.	cm	2.54
MASS	lbm	gm	453.59237
TEMPERATURE	^{o}R	K	5/9
FORCE	lbf	N	4.448222
VELOCITY	in./sec	cm/sec	2.54
PRESSURE	lbf/in.^{2}	MPa	0.006894757
DENSITY	lbm/in.^{3}	gm/cm^3	27.679905
COVOLUME	in.^{3}/lbm	cm^3/gm	0.036127292
INTERNAL ENERGY	lbf-in./lbm	J/gm	0.000249089
THERMAL CONDUCTIVITY	lbf-in./in.-sec-^{o}R	J/cm-sec-K	0.080068
THERMAL DIFFUSIVITY	in.^{2}/sec	cm^2/sec	6.4516
BURN RATE PRE-EXPONENT	in./sec-psi^n	cm/sec-MPa^n	$\frac{2.54}{(0.00689457)^n}$

NOVA CODE: COMPARISON INPUT DATA BASE

CONTROL PARAMETERS

PRINT	T
GRAPH	T
DISK WRITE	F
DISK READ	F
I.B. TABLE	T
FLAME TABLE	T
PRESSURE TABLES	T
EROSIVE EFFECT	0
DYNAMIC EFFECT	0
WALL TEMPERATURE CALCULATION	0
LEFT HAND BOUNDARY CONDITION	0
RIGHT HAND BOUNDARY CONDITION	0
LEFT HAND RESERVOIR	0
RIGHT HAND RESERVOIR	0
BED PRECOMPRESSED	0
HEAT LOSS CALCULATION	0
INSULATING LAYER	0
BORE RESISTANCE FUNCTION	0
EXPLICIT COMPACTION WAVE	0
MUZZLE BLOWDOWN ANALYSIS	0
CALCOMP SUMMARY PLOTS	0

INTEGRATION PARAMETERS

NUMBER OF STATIONS AT WHICH DATA ARE STORED	30
NUMBER OF STEPS BEFORE LOGOUT	100
TIME STEP FOR DISK START	0
NUMBER OF STEPS FOR TERMINATION	3000
TIME BEFORE PRINTOUT	.0005
PRESSURE RATIO FOR LP ANALYSIS OF LARGE ULLAGE REGION	.2
TIME FOR TERMINATION (SEC)	.05
PROJECTILE TRAVEL FOR TERMINATION (INS)	205.
MAXIMUM TIME STEP (SEC)	.0001
STABILITY SAFETY FACTOR	2.
SOURCE STABILITY FACTOR	.05
SPATIAL RESOLUTION FACTOR	.01
TIME INTERVAL FOR I.B. TABLE STORAGE (SEC)	.0002
TIME INTERVAL FOR PRESSURE TABLE STORAGE (SEC)	.0002

FILE COUNTERS

NUMBER OF STATIONS TO SPECIFY TUBE RADIUS	3
NUMBER OF TIMES TO SPECIFY PRIMER DISCHARGE	3
NUMBER OF POSITIONS TO SPECIFY PRIMER DISCHARGE	3

FILE COUNTERS (CONTINUED)

NUMBER OF ENTRIES IN BORE RESISTANCE TABLE	7
NUMBER OF ENTRIES IN WALL TEMPERATURE TABLE	0
NUMBER OF ENTRIES IN FILLER ELEMENT TABLE	0
NUMBER OF TYPES OF PROPELLANTS	1
NUMBER OF BURN RATE DATA SETS	2
NUMBER OF ENTRIES IN VOID FRACTION TABLES	0 0 0
NUMBER OF ENTRIES IN PRESSURE HISTORY TABLES	3
NUMBER OF ENTRIES IN LEFT BOUNDARY SOURCE TABLE	0
NUMBER OF ENTRIES IN RIGHT BOUNDARY SOURCE TABLE	0
NUMBER OF WALL STATIONS FOR INVARIANT EMBEDDING	0
NUMBER OF BED STATIONS FOR INVARIANT EMBEDDING	0

GENERAL PROPERTIES OF INITIAL AMBIENT GAS

INITIAL TEMPERATURE (DEG R)	530.
INITIAL PRESSURE (PSI)	14.7
MOLECULAR WEIGHT (LBM/LBMOL)	23.36
RATIO OF SPECIFIC HEATS	1.243

GENERAL PROPERTIES OF PROPELLANT BED

INITIAL TEMPERATURE (DEG R)	530.
VIRTUAL MASS COEFFICIENT FOR MOMENTUM TRANSFER	0.
VIRTUAL MASS COEFFICIENT FOR ENERGY DISSIPATION	0.
MINIMUM IMPACT VELOCITY FOR EXPLICIT COMPACTION WAVE (IN/SEC)	100000000.
FRICTION FACTOR	1.75

PROPERTIES OF PROPELLANT 1

PROPELLANT TYPE	M30A1, RAD-77G-069805
MASS OF PROPELLANT (LBM)	26.15
DENSITY OF PROPELLANT (LBM)	.0572
FORM FUNCTION INDICATOR	7
OUTSIDE DIAMETER (INS)	.4173
INSIDE DIAMETER (INS)	.0338
LENGTH (INS)	.9481
NUMBER OF PERFORATIONS	7.
SLOT WIDTH (INS)	0.

RHEOLOGICAL PROPERTIES

SPEED OF COMPRESSION WAVE IN SETTLED BED (IN/SEC)	6000.
SETTLING POROSITY	.4243
SPEED OF EXPANSION WAVE (IN/SEC)	50000.

SOLID PHASE THERMOCHEMISTRY

MAXIMUM PRESSURE FOR BURN RATE DATA (LBF/IN**2)	10000.
BURNING RATE PRE-EXPONENTIAL FACTOR (IN/SEC/PSI**BN)	.006918
BURNING RATE EXPONENT	.6337
MAXIMUM PRESSURE FOR BURN RATE DATA (LBF/IN**2)	100000.
BURNING RATE PRE-EXPONENTIAL FACTOR (IN/SEC/PSI**BN)	.001743
BURNING RATE EXPONENT	.7864
BURNING RATE CONSTANT	0.
IGNITION TEMPERATURE (DEG R)	800.
ARRHENIUS ACTIVATION ENERGY (LBF-IN/LBMOL)	0.
FREQUENCY FACTOR (SEC**-1)	0.
THERMAL CONDUCTIVITY (LBF/SEC/DEG R)	.02
THERMAL DIFFUSIVITY (IN**2/SEC)	.0003
EMMISIVITY FACTOR	0.

GAS PHASE THERMOCHEMISTRY

CHEMICAL ENERGY RELEASED IN BURNING (LBF-IN/LBM)	17600000.
MOLECULAR WEIGHT (LBM/LBMOL)	23.36
RATIO OF SPECIFIC HEATS	1.243
COVOLUME	28.50

LOCATION OF PACKAGE(S)

PACKAGE	LEFT BDDY (INS)	RIGHT BDDY (INS)	MASS (LBM)
1	1.00	31.00	26.15

PROPERTIES OF IGNITER

CHEMICAL ENERGY RELEASED IN BURNING (LBF-IN/LBM)	10000000.
MOLECULAR WEIGHT (LBM/LBMOL)	23.36
RATIO OF SPECIFIC HEATS	1.243
SPECIFIC VOLUME OF SOLID (IN**3/LBM)	0.

IGNITER DISCHARGE FUNCTION (LBM/IN/SEC)

POS. (INS)	0.00	0.98	0.99
TIME (SEC)			
0.000	6.00	6.00	0.00
0.010	6.00	6.00	0.00
0.011	0.00	0.00	0.00

PARAMETERS TO SPECIFY TUBE GEOMETRY

DISTANCE (INS)	RADIUS (INS)
0.00	3.50
35.00	3.09
240.00	3.09

BORE RESISTANCE TABLE

POSITION (INS)	RESISTANCE (PSI)
35.00	250.
35.40	3350.
36.00	4950.
36.55	3625.
37.05	3250.
39.50	2500.
240.00	1500.

THERMAL PROPERTIES OF TUBE

THERMAL CONDUCTIVITY (LBF/SEC/DEG R)	0.
THERMAL DIFFUSIVITY (IN**2/SEC)	0.
EMISSIVITY FACTOR	0.
INITIAL TEMPERATURE (DEG R)	530.

PROJECTILE AND RIFLING DATA

INITIAL POSITION OF BASE OF PROJECTILE (INS)	35.00
MASS OF PROJECTILE (LBM)	103.00
POLAR MOMENT OF INERTIA (LBM-IN**2)	0.
ANGLE OF RIFLING (DEG)	0.

POSITIONS FOR PRESSURE TABLE STORAGE (INS)

0.10	17.50	34.75

TDNOVA CODE: COMPARISON INPUT DATA BASE

CONTROL PARAMETERS

NPRINT (0=NO PRINT,1=PRINT)	1
NSUMRY (0=NO SUMMARY TABLES,1=YES)	1
NPLOT (0=NO ISOMETRIC CARPET PLOTS,1=PLOT)	1
NVHL (0=HIDDEN LINES DELETED,1=RETAINED)	0
NPLCON (0=NO CONTOUR PLOTS,1=PLOT)	0
NPLFLO (0=NO FLOW PLOTS,1=PLOT)	0
NPLFLM (0=NO FLAMESPREAD PLOT,1=PLOT)	1
NDSKW (0=NO DISC SAVE,1=DISC SAVE)	0
NDSKR (0=NO DISC START,>0=DISC START AT STEP NDSKR)	0

ISOMETRICALLY PLOTTED QUANTITIES (0=NO,1=YES)

MESH	0
POROSITY	0
GRANULAR STRESS	0
PRESSURE	1
DENSITY	0
GAS AXIAL VELOCITY	0
SOLID AXIAL VELOCITY	0
GAS RADIAL VELOCITY	0
SOLID RADIAL VELOCITY	0
GAS TEMPERATURE	1
PARTICLE SURFACE TEMPERATURE	0

CONTOUR PLOTTED QUANTITIES (0=NO,1=YES)

MESH	0
POROSITY	0
GRANULAR STRESS	0
PRESSURE	0
DENSITY	0
GAS AXIAL VELOCITY	0
SOLID AXIAL VELOCITY	0
GAS RADIAL VELOCITY	0
SOLID RADIAL VELOCITY	0
GAS TEMPERATURE	0
PARTICLE SURFACE TEMPERATURE	0

SCALE FACTOR FOR PLOTTING	.4
LENGTH OF Z-AXIS IN CALCOMP PLOTS (INS)	12.
LENGTH OF R-AXIS (INS)	4.
LENGTH OF ORDINATE AXIS (INS)	5.

LOGOUT PARAMETERS

NUMBER OF STEPS BEFORE LOGOUT	2000
TIME INCREMENT BEFORE LOGOUT (MSEC)	.5
NUMBER OF PRESSURE SUMMARY STATIONS	3
TIME INCREMENT FOR PRESSURE SUMMARY STORAGE (MSEC)	.2

TERMINATION PARAMETERS

MAXIMUM NUMBER OF STEPS BEFORE TERMINATION	2000
MAXIMUM INTEGRATION TIME (MSEC)	25.
MAXIMUM PROJECTILE TRAVEL (CMS)	520.7

MESH PARAMETERS

MESH ALLOCATION MODE (0=STATIC,1=DYNAMIC)	0
MAXIMUM NUMBER OF STORAGE POINTS FOR DYNAMIC MESH ALLOCATION	0
NUMBER OF MESH POINTS IN AXIAL DIRECTION	30
NUMBER OF MESH POINTS IN RADIAL DIRECTION	7
NUMBER OF ITERATIONS TO DETERMINE INITIAL MESH	200
SAFETY FACTOR FOR C-F-L CRITERION	1.1
MAXIMUM FRACTIONAL DISPLACEMENT FOR CONVERGENCE OF INITIAL MESH DISTRIBUTION	.00001
OVER-RELAXATION FACTOR FOR DETERMINATION OF INITIAL MESH DISTRIBUTION	1.6
PRESSURE TOLERANCE FACTOR FOR REDUCTION TO QUASI-TWO-DIMENSIONAL REPRESENTATION	.05
AXIAL SPATIAL RESOLUTION FACTOR	.1
RADIAL SPATIAL RESOLUTION FACTOR	.1

AMBIENT CONDITIONS

INITIAL TEMPERATURE (DEG K)	294.4
INITIAL PRESSURE (MPA)	.1014
CHARGE STANDOFF (CMS)	0.

SOLID PHASE CONSTITUTIVE DATA

INITIAL MASS OF GRANULAR BED (KG)	11.86
INITIAL POROSITY OF GRANULAR BED	0.
SETTLING POROSITY OF GRANULAR BED	.4243
SPEED OF COMPRESSION WAVE (M/SEC)	152.4
SPEED OF EXPANSION WAVE (M/SEC)	1270.0
DENSITY OF SOLID PHASE (GM/CC)	1.583
THERMAL CONDUCTIVITY (J/CM-SEC-DEG K)	.0016
THERMAL DIFFUSIVITY (CM**2/SEC)	.0006

GAS PHASE CONSTITUTIVE DATA

RATIO OF SPECIFIC HEATS	1.243
MOLECULAR WEIGHT (GM/GM-MOL)	23.36
COVOLUME (CC/GM)	1.030

SOLID PHASE COMBUSTION CHARACTERISTICS

IGNITION TEMPERATURE (DEG K)	444.4
CHEMICAL ENERGY (J/GM)	4384.

MAX PRESSURE (MPA)	ADD CONSTANT (CM/SEC)	PRE-EXPONENT (CM/SEC-MPA**BN)	EXPONENT
68.95	0.	.4117	.6337
689.50	0.	.2218	.7864

GRAIN GEOMETRY

EXTERNAL DIAMETER (CM)	1.060
LENGTH (CM)	2.408
DIAMETER OF PERFORATIONS (CM)	.086
NUMBER OF PERFORATIONS	7.

AX POS (CMS)	RAD POS (CMS)	FLOW RES DATA	REACTIVITY DATA	NO. PTS PRE-ASS.	DATA TYPE (0=D,1=N)
CONFIGURATION OF REAR OF BAG					
2.54	0.00	0	0	0	0
2.54	8.86	0	0	0	0
CONFIGURATION OF FRONT OF BAG					
78.74	0.00	0	0	0	0
78.74	7.97	0	0	0	0
CONFIGURATION OF INSIDE OF BAG					
2.54	0.00	0	0	0	0
78.74	0.00	0	0	0	0
CONFIGURATION OF OUTSIDE OF BAG					
2.54	8.86	0	0	0	0
78.74	7.97	0	0	0	0

AXIAL POSITION (CMS)	RADIAL POSITION (CMS)

CONFIGURATION OF BREECH

0.00	0.00
0.00	8.89

CONFIGURATION OF PROJECTILE BASE

88.90	0.00
88.90	7.85

CONFIGURATION OF INSIDE BOUNDARY

0.00	0.00
88.90	0.00

CONFIGURATION OF OUTSIDE BOUNDARY

0.00	8.89
88.90	7.85

REPRESENTATION OF IGNITION TRAIN

NCCORE (0=NO CENTERCORE,1=YES)	0
BASEPAD REACTIVITY DATA	0
NTABAG (0=NO EXTERNAL STIMULUS,1=YES)	1

CHEMICAL ENERGY OF EXTERNAL STIMULUS (J/GM) 2491.

RATE OF DISCHARGE OF EXTERNAL STIMULUS

RATE (GM/CC/SEC) AT TIME 0.00 MSEC

	RADIAL LOCATION (CM)		
AXIAL LOCATION (CM)	0.00	8.82	8.84
0.00	4.65	4.65	0.00
2.50	4.65	4.65	0.00
2.52	0.00	0.00	0.00

RATE OF DISCHARGE OF EXTERNAL STIMULUS (CONTINUED)

RATE (GM/CC/SEC) AT TIME 10.00 MSEC

AXIAL LOCATION (CM)	RADIAL LOCATION (CM) 0.00	8.82	8.84
0.00	4.65	4.65	0.00
2.50	4.65	4.65	0.00
2.52	0.00	0.00	0.00

RATE (GM/CC/SEC) AT TIME 11.00 MSEC

AXIAL LOCATION (CM)	RADIAL LOCATION (CM) 0.00	8.82	8.84
0.00	0.00	0.00	0.00
2.50	0.00	0.00	0.00
2.52	0.00	0.00	0.00

PROPERTIES OF PROJECTILE

PROJECTILE MASS (KG)	46.72
NUMBER OF ENTRIES IN BORE RESISTANCE TABLE	7
RESISTANCE LAW NUMBER	1
NUMBER OF FILLER ELEMENTS	0

BORE RESISTANCE DATA

PROJECTILE TRAVEL (CMS)	RESISTIVE PRESSURE (MPA)
0.000	1.72
1.016	23.10
2.540	34.10
3.937	25.00
5.207	22.40
11.430	17.20
520.700	10.30

LOCATION OF POINTS FOR PRESSURE SUMMARY TABLE

AXIAL LOCATION (CMS)	WALL (0) OR AXIS (1)
.25	0
44.45	0
88.27	0

APPENDIX B

INPUT DATA FOR TDNOVA P_{tol} AND MESH-SENSITIVITY CALCULATIONS

TDNOVA CODE: P_{tol} AND MESH STUDY DATA BASE

CONTROL PARAMETERS

NPRINT (0=NO PRINT,1=PRINT)	1
NSUMRY (0=NO SUMMARY TABLES,1=YES)	2
NPLOT (0=NO ISOMETRIC CARPET PLOTS,1=PLOT)	1
NVHL (0=HIDDEN LINES DELETED,1=RETAINED)	0
NPLCON (0=NO CONTOUR PLOTS,1=PLOT)	0
NPLFLO (0=NO FLOW PLOTS,1=PLOT)	0
NPLFLM (0=NO FLAMESPREAD PLOT,1=PLOT)	1
NDSKW (0=NO DISC SAVE,1=DISC SAVE)	0
NDSKR (0=NO DISC START,>0=DISC START AT STEP NDSKR)	0

ISOMETRICALLY PLOTTED QUANTITIES (0=NO,1=YES)

MESH	0
POROSITY	0
GRANULAR STRESS	0
PRESSURE	1
DENSITY	0
GAS AXIAL VELOCITY	0
SOLID AXIAL VELOCITY	0
GAS RADIAL VELOCITY	0
SOLID RADIAL VELOCITY	0
GAS TEMPERATURE	1
PARTICLE SURFACE TEMPERATURE	0

CONTOUR PLOTTED QUANTITIES (0=NO,1=YES)

MESH	0
POROSITY	0
GRANULAR STRESS	0
PRESSURE	0
DENSITY	0
GAS AXIAL VELOCITY	0
SOLID AXIAL VELOCITY	0
GAS RADIAL VELOCITY	0
SOLID RADIAL VELOCITY	0
GAS TEMPERATURE	0
PARTICLE SURFACE TEMPERATURE	0

SCALE FACTOR FOR PLOTTING	.4
LENGTH OF Z-AXIS IN CALCOMP PLOTS (INS)	12.
LENGTH OF R-AXIS (INS)	4.
LENGTH OF ORDINATE AXIS (INS)	5.

LOGOUT PARAMETERS

NUMBER OF STEPS BEFORE LOGOUT	2000
TIME INCREMENT BEFORE LOGOUT (MSEC)	.5
NUMBER OF PRESSURE SUMMARY STATIONS	3
TIME INCREMENT FOR PRESSURE SUMMARY STORAGE (MSEC)	.2

TERMINATION PARAMETERS

MAXIMUM NUMBER OF STEPS BEFORE TERMINATION	2000
MAXIMUM INTEGRATION TIME (MSEC)	25.
MAXIMUM PROJECTILE TRAVEL (CMS)	520.7

MESH PARAMETERS

MESH ALLOCATION MODE (0=STATIC,1=DYNAMIC)	0
MAXIMUM NUMBER OF STORAGE POINTS FOR DYNAMIC MESH ALLOCATION	0
NUMBER OF MESH POINTS IN AXIAL DIRECTION	VARIOUS
NUMBER OF MESH POINTS IN RADIAL DIRECTION	VARIOUS
NUMBER OF ITERATIONS TO DETERMINE INITIAL MESH	200
SAFETY FACTOR FOR C-F-L CRITERION	1.1
MAXIMUM FRACTIONAL DISPLACEMENT FOR CONVERGENCE OF INITIAL MESH DISTRIBUTION	.00001
OVER-RELAXATION FACTOR FOR DETERMINATION OF INITIAL MESH DISTRIBUTION	1.6
PRESSURE TOLERANCE FACTOR FOR REDUCTION TO QUASI-TWO-DIMENSIONAL REPRESENTATION	VARIOUS
AXIAL SPATIAL RESOLUTION FACTOR	.1
RADIAL SPATIAL RESOLUTION FACTOR	.1

AMBIENT CONDITIONS

INITIAL TEMPERATURE (DEG K)	294.4
INITIAL PRESSURE (MPA)	.1014
CHARGE STANDOFF (CMS)	0.

SOLID PHASE CONSTITUTIVE DATA

INITIAL MASS OF GRANULAR BED (KG)	11.86
INITIAL POROSITY OF GRANULAR BED	0.
SETTLING POROSITY OF GRANULAR BED	0.
SPEED OF COMPRESSION WAVE (M/SEC)	152.4
SPEED OF EXPANSION WAVE (M/SEC)	1270.0
DENSITY OF SOLID PHASE (GM/CC)	1.583
THERMAL CONDUCTIVITY (J/CM-SEC-DEG K)	.0016
THERMAL DIFFUSIVITY (CM**2/SEC)	.0006

GAS PHASE CONSTITUTIVE DATA

RATIO OF SPECIFIC HEATS	1.243
MOLECULAR WEIGHT (GM/GM-MOL)	23.36
COVOLUME (CC/GM)	1.030

SOLID PHASE COMBUSTION CHARACTERISTICS

IGNITION TEMPERATURE (DEG K)	444.4
CHEMICAL ENERGY (J/GM)	4384.

MAX PRESSURE (MPA)	ADD CONSTANT (CM/SEC)	PRE-EXPONENT (CM/SEC-MPA**BN)	EXPONENT
68.95	0.	.4117	.6337
689.50	0.	.2218	.7864

GRAIN GEOMETRY

EXTERNAL DIAMETER (CM)	1.060
LENGTH (CM)	2.408
DIAMETER OF PERFORATIONS (CM)	.086
NUMBER OF PERFORATIONS	7.

AX POS (CMS)	RAD POS (CMS)	FLOW RES DATA	REACTIVITY DATA	NO. PTS PRE-ASS.	DATA TYPE (0=D,1=N)
CONFIGURATION OF REAR OF BAG					
2.54	1.27	1	1	0	0
2.54	3.40	1	0	0	0
2.54	7.62	0	0	0	0
CONFIGURATION OF FRONT OF BAG					
78.74	1.27	2	0	0	0
78.74	7.62	0	0	0	0
CONFIGURATION OF INSIDE OF BAG					
2.54	1.27	3	0	0	0
78.74	1.27	0	0	0	0
CONFIGURATION OF OUTSIDE OF BAG					
2.54	7.62	1	0	0	0
27.94	7.62	4	0	0	0
78.74	7.62	0	0	0	0

AXIAL POSITION (CMS)	RADIAL POSITION (CMS)
CONFIGURATION OF BREECH	
0.00	0.00
0.00	7.06
-3.45	8.48
CONFIGURATION OF PROJECTILE BASE	
87.38	0.00
87.38	7.14
96.42	7.85
CONFIGURATION OF INSIDE BOUNDARY	
0.00	0.00
87.38	0.00
CONFIGURATION OF OUTSIDE BOUNDARY	
-3.45	8.48
92.46	8.05
96.42	7.85

REPRESENTATION OF IGNITION TRAIN

NCCORE (0=NO CENTERCORE,1=YES)	1
BASEPAD REACTIVITY DATA	1
NTABAG (0=NO EXTERNAL STIMULUS,1=YES)	0

PROPERTIES OF SOLID PHASE IN CENTERCORE

SOLID PHASE CONSTITUTIVE DATA

INITIAL MASS OF GRANULAR BED (KG)	.1134
INITIAL POROSITY OF GRANULAR BED	0.
SETTLING POROSITY OF GRANULAR BED	.40
SPEED OF COMPRESSION WAVE (M/SEC)	442.
SPEED OF EXPANSION WAVE (M/SEC)	1270.
DENSITY OF SOLID PHASE (GM/CC)	1.799
THERMAL CONDUCTIVITY (J/CM-SEC-DEG K)	.0016
THERMAL DIFFUSIVITY (CM**2/SEC)	.0006

SOLID PHASE COMBUSTION CHARACTERISTICS

IGNITION TEMPERATURE (DEG K)	300.
CHEMICAL ENERGY (J/GM)	2489.

MAX PRESSURE (MPA)	ADD CONSTANT (CM/SEC)	PRE-EXPONENT (CM/SEC-MPA**BN)	EXPONENT
.52	0.	2.508	.4620
690.00	0.	2.007	.1330

GRAIN GEOMETRY

EXTERNAL DIAMETER (CM)	.3
LENGTH (CM)	0.
DIAMETER OF PERFORATIONS (CM)	0.
NUMBER OF PERFORATIONS	0.

PROPERTIES OF PROJECTILE

PROJECTILE MASS (KG)	46.72
NUMBER OF ENTRIES IN BORE RESISTANCE TABLE	7
RESISTANCE LAW NUMBER	1
NUMBER OF FILLER ELEMENTS	0

BORE RESISTANCE DATA

PROJECTILE TRAVEL (CMS)	RESISTIVE PRESSURE (MPA)
0.000	1.72
1.016	23.10
2.540	34.10
3.937	25.00
5.207	22.40
11.430	17.20
520.700	10.30

BAG FLOW RESISTANCE DATA

TYPE	INIT FRICTION FACTOR	RUPTURE STRESS (MPA)	RUPTURE INTERVAL (MSEC)
1	.01	.30	0.0
2	101.00	.60	0.0
3	101.00	.60	2.0
4	101.00	.30	0.0

DATA TO DESCRIBE REACTIVITY OF BAG SUBSTRATE 1

ENERGY RELEASED DURING DECOMPOSITION (J/GM) 2489.

BAG SUBSTRATE DISCHARGE CHARACTERISTICS

TIME (MSEC)	RATE OF DISCHARGE (GM/CM**2-SEC)
0.0	2.62
0.1	26.20
30.0	26.20

LOCATION OF POINTS FOR PRESSURE SUMMARY TABLE

AXIAL LOCATION (CMS)	WALL (0) OR AXIS (1)
.25	0
44.45	0
88.27	0

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